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## Attunement and Affordance Learning in Infants

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### ABSTRACT

From a perceptual learning perspective, infants use social information (like gaze direction) in a similar way as other information in our physical environment (like object movements) to specify action possibilities. In the current study, we assumed that infants are able to learn an affordance upon observing an adult failing to act out that affordance, without appreciating object-directed intentions, or, communicative intent towards the infant. Using a variation of the Re-enactment procedure, we found that when the attention of infants ( $N = 46$ ,  $M_{age} = 20$  months) was drawn towards the eyes of the person before she acted out the failed attempt, either by ostensive cues or non-ostensive cues, infants achieved more affordances than when their attention was not directed towards the eyes. As directing the attention of infants to the eyes of another person frequently results in gaze following, this suggests that infants use the gaze direction of another person in order to learn what affordance that other person is trying to realize. In addition, the results of a spatiotemporal analysis on the eye-movements of infants suggest that the gaze and the object movements of the person facilitate learning by directing the attention of infants towards important object-directed actions on crucial moments during the failed attempt demonstrations. These results are discussed in terms of perceptual attunement and affordance learning.

### Introduction

Adults tend to actively facilitate learning contexts for infants such that it allows them to acquire skills like the use of tools, language and cultural practices (Tomasello, 1999). These learning contexts are commonly facilitated by directing the attention of infants towards objects of interest (by means of, e.g. pointing and gaze) and by demonstrating the way how certain objects or tools can be used (e.g. Gergely, Bekkering, & Király, 2002; Hopper, 2010; Király, 2009; Meltzoff, 1995; Nielsen, 2006; Southgate, Chevallier, & Csibra, 2009). A longstanding debate is whether infants need to understand or interpret these ostensive signals as communicative or infer someone's intentions or goals while that person demonstrates how certain objects can be used, in order to learn from that person effectively (Csibra & Gergely, 2009; de Bordes, Cox, Hasselman, & Cillessen, 2013; Doherty, 2006; Haith, 1998; Heyes, 2012, 2016; Hopper, 2010; Paulus, 2011; Want & Harris, 2002). In developmental research, learning by infants in non-social situations has

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been frequently explained by what aspects of the task or the task materials infants need to understand in order to produce a certain goal (e.g. Dejonckheere, Smitsman, & Verhofstadt-Denève, 2007; Huang & Charman, 2005; Thelen, Schöner, Scheier, & Smith, 2001). Conversely, superior learning outcomes in social settings are usually explained in terms of what infants understand of the (social) behavior of others (e.g. Topál, Gergely, Miklósi, Erdőhegyi, & Csibra, 2008; see Hopper, 2010 for an overview). Although it seems straightforward that infants do not need to understand the (social) behavior of others when they successfully learn something in non-social contexts, relatively few studies have assessed how infants can learn from others without them having mentalistic assumptions about that other person (Goldstein & Schwade, 2008; also see Hellendoorn, 2014; Heyes, 2012). Therefore, the current study sought to identify a non-mentalistic and perceptual basis for how infants can learn certain affordances when an adult draws their attention towards objects and demonstrates how they can be used. An affordance in this sense is defined as an action possibility provided by the social and/or material environment given the action capabilities of the infant (also see Gibson, 1986, 1988; Gibson & Pick, 2000; Ishak, Franchak, & Adolph, 2014; Michaels & Carello, 1981).

In Meltzoff (1995) study, 18-month-olds viewed a woman acting out either a failed attempt or a successful attempt in combining several object pairs after which they tended to combine the object pairs successfully in both conditions at similar rates. Meltzoff reasoned that as the infants had never seen the fulfilled object-directed actions in the failed attempt demonstration, they must have been able to detect the model's intended goal that they subsequently imitated (Meltzoff, 1995; for similar findings, see Bellagamba & Tomasello, 1999; Danish & Russell, 2007; Johnson, Booth, & O'Hearn, 2001). As an alternative to this interpretation of the data, Huang and Charman (2005) have suggested that the object movements in the demonstrations might contain sufficient perceptual information for infants to realize the affordance as an action possibility (i.e. the goal or end-state of the task). Huang and Charman (2005, experiment 3) introduced a non-social 'ghost' condition of the task used by Meltzoff (1995) in which they showed infants a demonstration of the failed attempt where the actor handling the objects was not visible. It was found that the success rate of infants realizing the affordance after having watched the object movement demonstration was similar to the success rate after watching a failed attempt demonstration in which a model acted out the object-directed actions. They concluded, therefore, that mental state attribution or interpreting social cues is not necessary for infants to realize the target affordance under these conditions (for similar findings, see Horne, Erjavec, & Lovett, 2009; Huang, Heyes, & Charman, 2002; Shneidman, Todd, & Woodward, 2014; Thompson & Russell, 2004). According to Huang and Charman (2005), a perceptual mechanism that might enable infants to realize the target affordance after seeing the failed attempt demonstration or the 'ghost' failed attempt demonstration could be *stimulus enhancement* (also see Charman & Huang, 2002).

Stimulus enhancement is a concept used in both developmental and comparative research and refers to the process in which the attention of a person or animal is drawn towards an object or object part, simply because someone or something is interacting with that object, increasing the chance that the observer will interact with that object or object part thereafter (e.g. Fritz, Bisenberger, & Kotrschal, 2000; Heyes, Ray, Mitchell, & Nokes, 2000; Hopper, 2010; Hoppitt & Laland, 2013; Horne et al., 2009; Huang & Charman, 2005; Huang et al., 2002; Want & Harris, 2002; Zentall, 2001). In Huang and Charman's (2005)

non-social ‘ghost’ condition, the object movements and the way the object pairs were brought in close proximity apparently specified the appropriate action possibilities for the infants (i.e. how they can be combined in specific ways). This enabled most of them (but not all) to realize the target affordance. This suggests that stimulus enhancement can specify affordances for those objects without the necessity to perceive the completion of the actions afforded by those objects. Interestingly, most infants in the study by Meltzoff (1995) realized the target affordance after seeing the failed attempt demonstration, but not after they viewed someone handling the objects in a non-specific way during the adult manipulation demonstration. During the failed attempt demonstration, relevant parts of the objects were manipulated with the relevant actions (e.g. conveying a stick towards a hole in which it can be placed), whereas this was not the case during the adult manipulation demonstration (e.g. picking up the stick and placing it on the table), leading infants in the former but not the latter condition to realize the target affordances (Charman & Huang, 2002). This suggests that affordance learning can occur through stimulus enhancement as long as it *specifies* a certain action possibility to the observer in relation to the stimulus as opposed to guiding the observer’s attention towards an object (part) in a more general (i.e. non-specifying) way. In this sense, the way stimulus enhancement leads to affordance learning closely resembles to what Gibson (1986) defined as ‘*education of attention*’ in which “the perceptual system is attuned to ‘picking up’ critical features of the environment” (Ingold, 2001, p. 137).

In our view, there are many ways in which attention can be attuned to critical features of the environment from which affordances can be learned. These can be social such as pointing and gaze (de Bordes et al., 2013; Goldin-Meadow, 2007), non-social such as handling or dropping an object (Fritz et al., 2000; Zentall, 2001), and inanimate such as mechanical movements (Dejonckheere et al., 2007) or animations (Grant & Spivey, 2003). In natural social situations, infants ranging between 12 and 18 months of age tend to look at the hand movements and the gaze of the caregiver from which they can learn about what the caregiver is doing and more general leads to joint attention (Yu & Smith, 2013, 2017). Infants in this age group (12 to 18 months of age) tend to follow the hand movements to a greater extent than gaze direction (Yu & Smith, 2013; also see Deák, Krasno, Jasso, & Triesch, 2018, for similar results across the age range of 3 to 11 months of age). They might follow hand movements to a greater extent than someone’s gaze because only from 18 months of age, infants can follow the direction of eye gaze reliably (Corkum & Moore, 1995; de Bordes et al., 2013). In addition, following hand movements seem more economic as that might be more indicative of what affordances someone is trying to realize rather than following gaze alone (see Yu & Smith, 2013, 2017). However, because gaze and hand movements are coupled (e.g. Adam, Buetti, & Kerzel, 2012), observing the gaze of another person can possibly provide additional information on what affordances that person is trying to realize than observing hand movements alone (also see Sebanz, Bekkering, & Knoblich, 2006). For instance, infants can use gaze direction in order to anticipate object-directed actions (Paulus, 2011), potentially leading them to observe (parts of) objects and locations on moments that are crucial for understanding the affordance that is being realized. Therefore, we suggest that observing the gaze of a person could support the perceptual system of infants in attuning to critical features of the environment, including certain object movements, by which affordances can be learned from that person, even when the fulfilled affordance is not observable, as is the case when demonstrating a failed attempt.

Gaze following can be instigated by attracting the attention of the infant towards the eye region of another person (e.g. de Bordes et al., 2013). Specifically, research has shown that whereas 6-month-olds can reliably follow *head turns* after their attention has been drawn towards the head of another person (Gredebäck, Astor, & Fawcett, 2018; Senju & Csibra, 2008; Szufnarowska, Rohlfing, Fawcett, & Gredebäck, 2014), 18- to 20-month-olds can use the affordance of follow *eye-movements* of another person when their attention has been drawn towards the eye-region, rather than the face in general (Corkum & Moore, 1995; de Bordes et al., 2013). In case of a failed attempt demonstration, in which the target affordance is not realized, attracting the attention of infants towards the eyes prior to a failed attempt demonstration could lead infants from 18 months of age to use the gaze of that person. This could direct their field of view towards the actions performed by the observed person in a more specifying manner than if they would look at the object movements alone, as suggested above. In the re-enactment procedure, for instance, observing someone looking towards the hole to which that person is conveying a stick might indicate that the stick can be placed in the hole.

In order to test the idea that gaze following promotes affordance learning when a model demonstrates certain object-directed actions, we used Meltzoff's (1995) failed attempt condition which does not include the end-state of the object-directed actions. We did not include the end-state of the object-directed actions in order to specifically assess affordance learning in this situation and not the mere reproduction of the goal as would be the case in goal emulation (Hopper, 2010). We varied the likelihood of infants following the gaze direction of the model during the failed attempt demonstration by manipulating the eye region of the model *immediately prior* to the demonstration, similar to de Bordes et al. (2013).

Specifically, we attracted infants' attention to the eyes of the model by leaving them either visible (Eye Contact condition) or by presenting moving and flashing dots on top of the eyes (Eye Salience condition). We added a third condition in which the models' face was covered completely with a flower animation (No Eye Contact condition), drawing attention to the facial region rather than the eyes alone. Following from our reasoning that gaze following assists infants in discovering the object affordance, we expected infants to have a bigger chance to realize the target affordance after their attention was drawn towards the model's eye region prior to the failed attempt demonstration than if their attention was directed towards the head region in a non-specific way. This would lead to higher success rates in the Eye Contact and Eye Salience conditions compared to the No Eye Contact condition. In addition, we expected no difference in gaze following and subsequent affordance realization between the Eye Contact and Eyes Salience conditions, which would replicate earlier findings of the attention modulating nature of gaze following (de Bordes et al., 2013; also see Gredebäck et al., 2018) and generalize it to the Re-enactment context.

An additional aim of this study was to explore the spatiotemporal structure of infant looking behavior, and how this is related to the specification of the target affordance, as a function of condition contrasts and whether they successfully realized the target affordance or not. To this end, we have included eye-tracking measures of the infants while they watched the failed attempt demonstrations. We speculated that infants who were successful at realizing the target affordance might be inclined to look at the object movements during times in which those object movements could specify the object affordance

whereas infants who were unsuccessful would look at the object movements in a more unspecific manner. Together, this will help us to better understand how hand movements and the gaze behavior of adults can specify affordances to infants in this context and how it relates to affordance learning in general.

## Method

### Participants

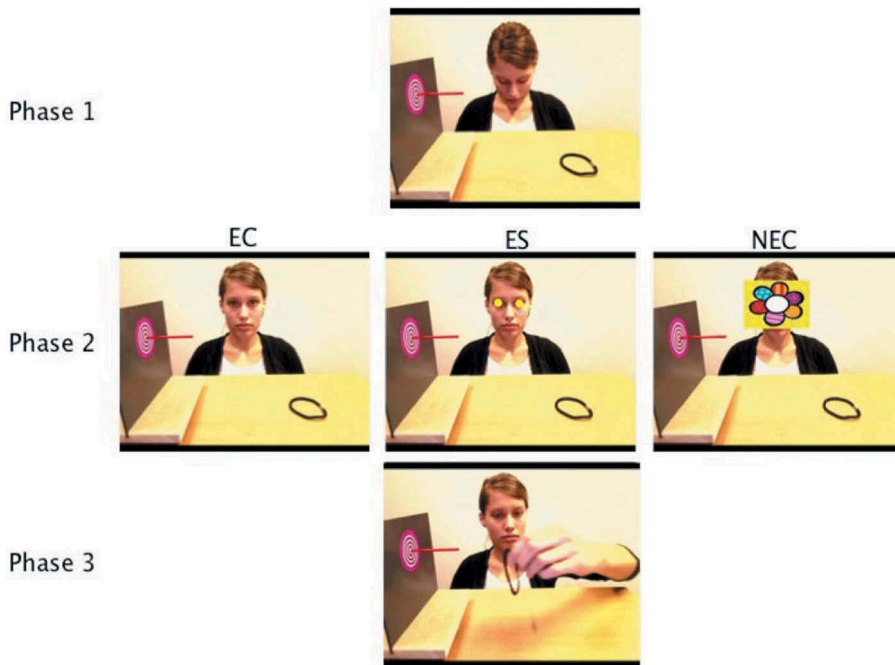
Addresses of 510 parents of 20-month-old infants in the city of Nijmegen, the Netherlands, were provided by local government authorities. A total of 61 parents (12%) responded to the invitation with a confirmation and signed informed consent. All 61 infants were included in the study ( $M_{age} = 20$  months and 2 days,  $SD = 17$  days; 30 girls and 31 boys).

### Stimulus material & procedure

Upon arrival, infants and parent(s) were brought to the testing room. After a brief warming-up period, infants sat on their parents' lap in a room with dimmed light, approximately 60 cm away from a 17-in. TFT monitor (60 Hz) with a built-in remote eye-tracking system (Tobii T120, Tobii Technology, Danderyd, Sweden). The 31.2 by 22.9-cm screen and the distance from it created a 30° by 21° visual angle with a screen resolution of 1280 × 1024. We used Clearview software (Version 2.7, Tobii Technology) to calibrate the eyes of the infants (on a nine-point calibration program), to present stimuli, and record eye movements of the infants. Before the experiment started, infants participated in another experiment reported elsewhere (de Bordes et al., 2013). Each trial was preceded by an attention grabber displaying colorful animations with bleeping sounds until the infants attended to the center of the screen. Trials consisted of videos of failed attempt demonstrations with a female model manipulating five different object pairs identical to those used in Meltzoff's (1995) study. The objects were 1) a dumbbell-shaped toy that could be pulled apart and put together again ('Dumbbell'), 2) a box with a hole in which a wooden stick could fit to activate a buzzer ('Box-Stick'), 3) a loop that could be draped over a horizontal prong that was attached to a vertically standing board ('Loop-Prong'), 4) a chain of beads that could be placed in a cylinder-shaped container ('Beads') and 5) a wooden square with a cylinder on top on which a plastic square with a round hole could be placed ('Square-Dowel'). A detailed description of the geometrical properties of these objects is given in Meltzoff (1995).

Each failed attempt demonstration was shown in three sequential phases (Figure 1). In the first phase, the model's face oriented downward for two seconds. In the second phase (manipulation phase), she looked up and straight ahead for two seconds. In this second phase, the same basic video was used for all three conditions but with modifications between them, creating different conditions across infants. In the *Eye Contact condition* (EC) the model moved her head up and looked straight ahead for two seconds (unmodified). In the *Eyes Salience condition* (ES) colorful blinking and moving dots overlaid the model's eyes during the time she looked up and straight ahead. This rendered the eyes themselves invisible but the eye region salient. In the *No Eye Contact condition* (NEC) a colorful animation of a flower overlaid her head of the model while she looked up and





**Figure 1.** The manipulation phases for each of the conditions EC, ES and NEC. Conditions across children only differed in phase 2.

straight ahead, obscuring the whole face region. The third phase was identical across conditions and consisted of the model acting out three failed attempts demonstrations in succession while having her hands, arms, torso and head in full display. This typically consisted of placing an object (i.e. dynamic object) closely to another object (i.e. static object) as will be explained below. After each demonstration (lasting for approximately seven seconds), the objects were restored to their initial position before the next demonstration begun (also called the ‘retrieval phase’) until three demonstrations were finished.

For the *Dumbbell*, the failed attempt consisted of the model picking up the object with both hands and attempting to pull one of the wooden blocks sideward. However, instead of the wooden block being detached from the stick this resulted in slipping of the fingers over the block and a lateral movement of only the hand in that direction. Slippage was alternated from the left to the right, and back to the left again. For the *Box-Stick*, the model would pick up the stick and move it towards the hole in the box, where it would land right next to the hole. In the first failed attempt, she placed the stick to the left side of the hole, in the second on the right side, and in the third-failed attempt, just above the hole. For the *Loop-Prong*, the model picked up the nylon loop, moved it towards the prong where she would drop the loop on the table. She first moved the loop to the left of the prong, then to the right, and finally below the prong. For the *Beads*, the model picked up the chain of beads and moved it towards the cylinder where she dropped the chain on the edge of the cylinder, after which the beads fell down on the table next to the cylinder. For the *Square-Dowel*, the model picked up the plastic square and placed it onto the dowel but failed to place the hole of the square over the cylinder on the dowel, so as to fit the objects together.



In all demonstrations, the model's eye gaze was always directed at the moving object until it approached the goal region on the stationary object. At that moment, the model's eye gaze was directed mainly at the goal region until the objects were placed back towards their initial location. To control for effects of laterality, the movement direction for each object was counterbalanced between infants. That is, half of the infants viewed a left-to-right movement on the second and fourth trial and a right-to-left movement on the first, third and fifth trial, whereas for the other half this was reversed. Immediately after each set of failed attempts, the screen went blank, and the experimenter placed the objects pairs on the table in front of the infant while uttering 'Look'. A small webcam (Sonix SN9C201, Taiwan) next to the screen recorded infants' behavior after each demonstration. After the five trials were finished, parents and infants were thanked for their cooperation and the parents were debriefed.

### ***Behavioral scoring and data reduction***

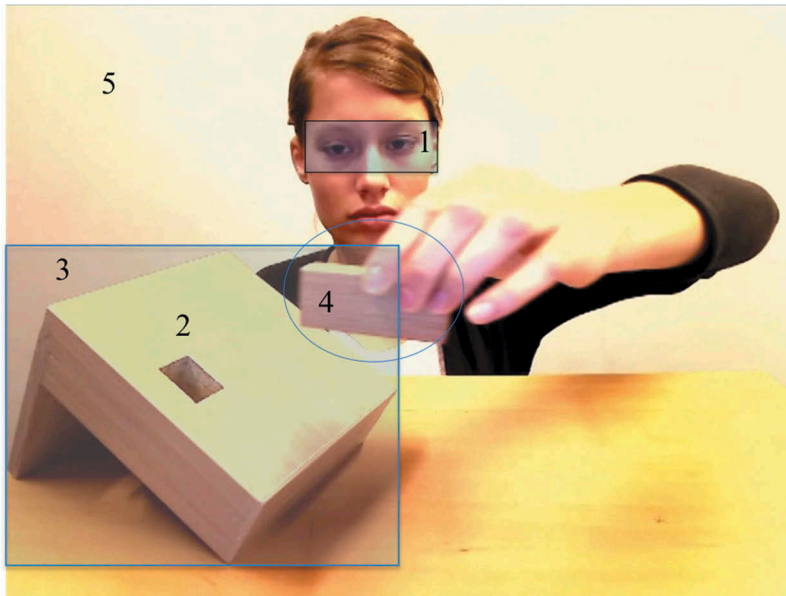
A total of 15 infants were excluded from the analysis due to experimenter error (1) or equipment failure (4), inattentiveness of the infant,<sup>1</sup> or refusal to touch one or more object pairs within the first 20 seconds (7) or interference by the parent (3). As a primary measure, we scored whether the remaining 46 infants with valid data performed the target act (yes/no) within a 20-second response period, starting when they first touched the object (similar to the studies reported by Bellagamba & Tomasello, 1999; Huang & Charman, 2005; Meltzoff, 1995). For the Dumbbell, the goals consisted of pulling one of the squares apart from the rest of the object. For the Box-Stick, the goal was to insert the stick into the box, which then would activate the buzzer inside. We noticed that infants experienced difficulties activating the buzzer, because the hole was too deep and/or the button inside too rigid. Therefore, we counted the behavior as correct whenever an infant placed the stick partly into the hole (i.e. when all four corners of the end of the stick were inside the hole). For the Loop-Prong, the goal was to drape the loop onto the prong. For the Beads, the goal was to place the chain of beads in the cylinder. Finally, for the Square-Dowel, the goal was to place the square onto the dowel. Next, we made proportion scores of the total amount of target acts completed per infant. Whether infants successfully produced the actions afforded by the object was scored live by an experimenter. In addition, one-third of the trials were scored after the data were collected by someone who was unaware of the goals of the study. There were no discrepancies between the two coders (Cohen's  $\kappa = 1$ ), meaning that successes and failures were clear. Finally, we measured the time in seconds infants needed to complete the target acts with the object pairs whenever they were successful.

### ***Eye-tracking measures; spatial regions of interest analysis***

In order to analyze what infants looked at during the failed attempt demonstrations with the different object pairs, we identified several regions of interest (ROI) in terms of x and y coordinates on the screen (see Figure 2). The ROI used were 1) the eye region of the model, 2) the complete static object in the scenery, 3) the specific region of the static

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<sup>1</sup>Some infants had a preference to explore the room or interact with the parent instead of attending to the experimental stimuli.



**Figure 2.** The regions of interest consisting of 1) the eye-region, 2) the goal region of the static object, 3) the whole static object, 4) the dynamic object and, 5) all else.

object that can be combined with the dynamic object (goal region), 4) the dynamic object that can be combined with the static object and finally, 5) all else. We tracked the movement of the dynamic object frame-by-frame across the demonstrations with different object pairs, using Adobe After Effects (Adobe After Effects CC, Adobe, 2015). Using MATLAB (MATLAB, Version 9), we registered to which ROI infants were looking on each timeframe at 60 Hz. Whenever there was an overlap in looking at the dynamic object and another ROI, only looking at the dynamic object was registered. The duration infants looked at each ROI during each failed attempt demonstration was calculated by adding up all timeframes in which infants looked at the pixel coordinates that corresponded with the ROI per object pair. Next, we averaged the looking time to each ROI across the object pairs for each infant that was used to calculate the percentages of looking time towards each ROI for infants in each condition. Only the object pairs ‘Box-Stick’, ‘Loop-Prong’ and ‘Beads’ were included in the eye-movement analysis because the demonstrations for these three object pairs extended across a large portion of the screen, eliciting clearer eye movements in the infants.

### ***Eye-tracking measures: spatiotemporal regions of interest analysis***

Individual time series of eye-movements were created by registering to which ROI each infant was looking at for each timeframe. Then, we collapsed these individual time series in percentages across conditions and according to whether infants realized the target affordance of not. These time series allowed us to perform a descriptive analysis on the spatiotemporal order in which infants looked at the different ROIs. Further, for each ROI at each timeframe for all infants, we calculated the 95% confidence intervals to assess whether infants in each condition would look at a certain ROI at a certain time significantly more than would be

expected from the total amount of infants included in this study. To this end, the percentages of infants looking at each ROI per time frame were first transformed into proportions within a Z-distribution. Next, difference score times series were created by subtracting the proportion of looking time at each ROI at each timeframe of unsuccessful infants from successful infants. The resulting difference score indicates in which time frames more successful infants looked at a particular ROI than unsuccessful infants (indicated by a positive proportion) and vice versa (indicated by a negative proportion). Then, a confidence interval of 95% was calculated for the percentage of infants looking at each ROI per time frame. This was subsequently used to compare the looking proportions to ROIs at each time frame for successful and unsuccessful infants across the three experimental conditions.

Finally, in order to determine whether condition type influenced these difference scores between correct and incorrect, a permutation test was applied to the following ROIs: 1) the eye region of the model, 2) the specific region of the static object that can be combined with the dynamic object (goal region), 3) the dynamic object that can be combined with the static object. The temporal order of values of the difference scores time series was resampled 999 times after which the rank of the observed difference score among the 999 resampled difference scores for each time point (i.e. ranging from 1 to 1000) was evaluated. Specifically, a p-value was calculated by dividing the number of difference scores that were equal to the observed difference or more extreme by the number of values in the distribution. The alpha level was adjusted from .05 by a factor 3 for multiple comparisons, taking into account that the looking at one of the three analyzed ROIs affects the timing and duration of looking to another ROI. Because the observed time series are autocorrelated, the method of random block size resampling (or, stationary bootstrap, cf. Politis & Romano, 1994) was applied. First, a time series is covered with blocks of different sizes that are randomly drawn from a geometric distribution (the mean expected block size was 4, this was based on an inspection of the partial autocorrelation functions of the observed time series, which had significant correlations up to lags of 3, 4 and 5). Second, the surrogate time series for the permutation tests is generated by randomizing the order of the blocks, preserving the temporal order of values within each block. Finally, the ranks of observed and surrogate differences are calculated, yielding a p-value for each timepoint (see, e.g. Vink, Hasselman, Cillessen, Wijnants, & Bosman, 2018).

## Results

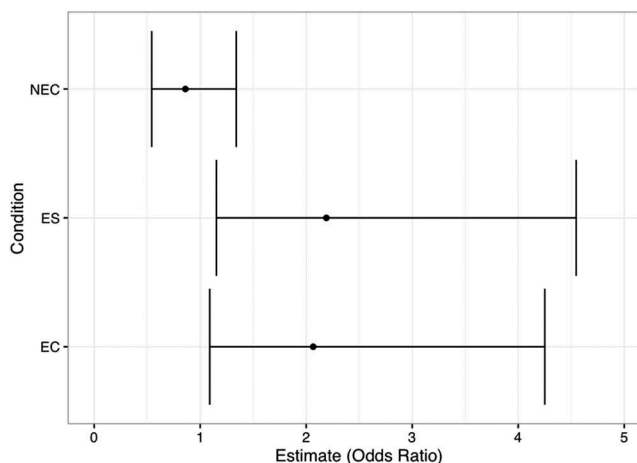
### *Behavioral measures*

Even though they had only seen failed attempts by the model, on average, infants in the EC (Eye Contact) condition correctly performed 64% of the actions afforded by the objects. Infants in the ES (Eye Saliency) and NEC (No Eye Contact) condition correctly performed 65% and 46% of the target acts, respectively. This overall success rate of performing the target acts across the conditions is comparable to Huang and Charman (2005, experiment 3, object movement failed attempt) and Huang, Heyes and Charman (2002, failed attempt condition). A simple regression analysis revealed that the proportion of target acts produced was not influenced by age, sex, or effects of laterality (*all predictors n.s.*).

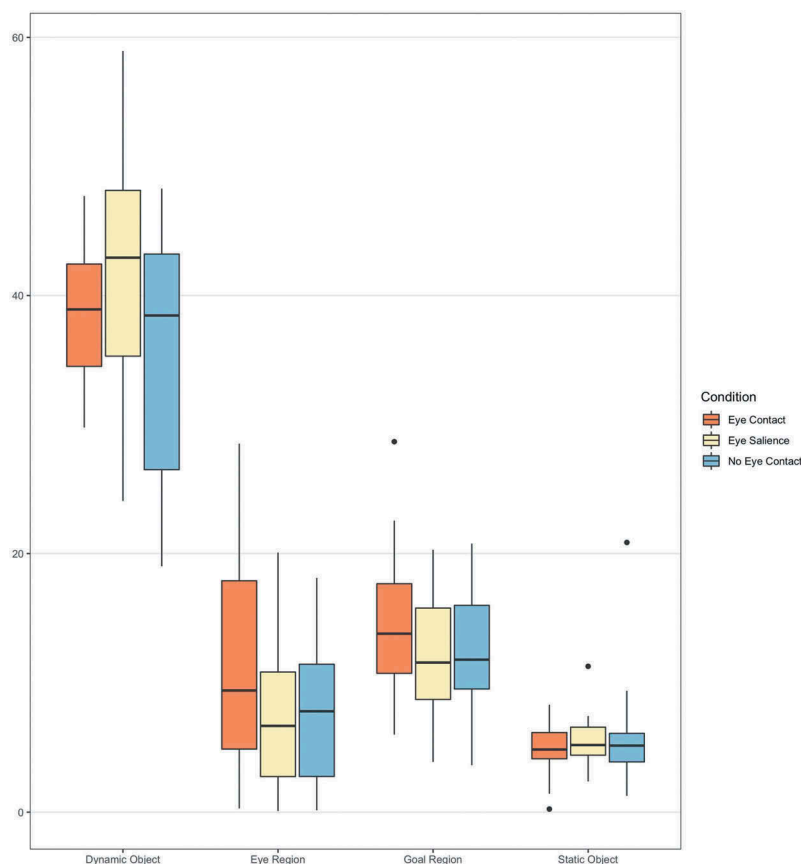
To test whether the proportion of target acts completed differed between conditions, we fitted mixed effects logistic model for binary outcomes (incorrect = 0, correct = 1) using the R package lme4 (Bates et al., 2014; R Core Team, 2016). Condition was entered as a fixed factor (taking NEC as the reference category) in a model with random intercepts for target objects and participants. The estimated odds of correctly performing the target action in the NEC condition did not deviate significantly from 50% ( $\beta_{\text{intercept}} = -0.15$ ,  $SE = 0.22$ , Wald  $Z = -0.67$ ,  $p = .5$ ,  $OR = 0.86$ , 95% CI [0.54, 1.29]). However, relative to the NEC condition, the odds of producing a correct action increased significantly for the EC condition ( $\beta = 0.73$ ,  $SE = 0.33$ , Wald  $Z = 2.21$ ,  $p = .02$ ,  $OR = 2.07$ , 95% CI [1.08, 4.29]) as well as the ES condition ( $\beta = 0.178$ ,  $SE = 0.33$ , Wald  $Z = 2.37$ ,  $p = .02$ ,  $OR = 2.19$ , 95% CI [1.22, 4.40]). The odds ratios did not differ across the ES and EC conditions, as can be seen in Figure 3, which displays the estimated OR with 95% bootstrapped confidence intervals for each condition. In addition, a mixed effect model with subjects and objects as random factors showed that infants in the EC condition and ES condition combined ( $M = 6.6$  seconds,  $SD = 3.4$  seconds) needed significantly less time to complete the target acts than infants in the NEC condition ( $M = 9.6$  seconds,  $SD = 4.8$  seconds) whenever infants made a successful attempt ( $\beta_{\text{EC+ES}} = -2.41$ ;  $SE = 1.13$ ; Satterthwaite's method:  $t(42.6) = -2.14$ ,  $p < .039$ ).

### Eye-tracking measures: spatial regions of interest analysis

As can be seen in Figure 4, there were no differences across conditions for the total amount of looking time to the different ROIs (all differences *n.s.*). This reveals that making the eyes of the model salient (naturally or artificially) or covering the whole face area prior to the failed attempt demonstration did not affect the duration of time infants spend looking at the different ROIs thereafter. In addition, we also did not find any difference in looking duration towards the ROIs during the failed attempt demonstrations between successful and unsuccessful attempts (all differences *n.s.*).



**Figure 3.** Odds Ratios of effect estimates of the mixed effects model for each of the conditions EC, ES and NEC with 95% bootstrap Confidence Intervals (1000 bootstrap simulations).

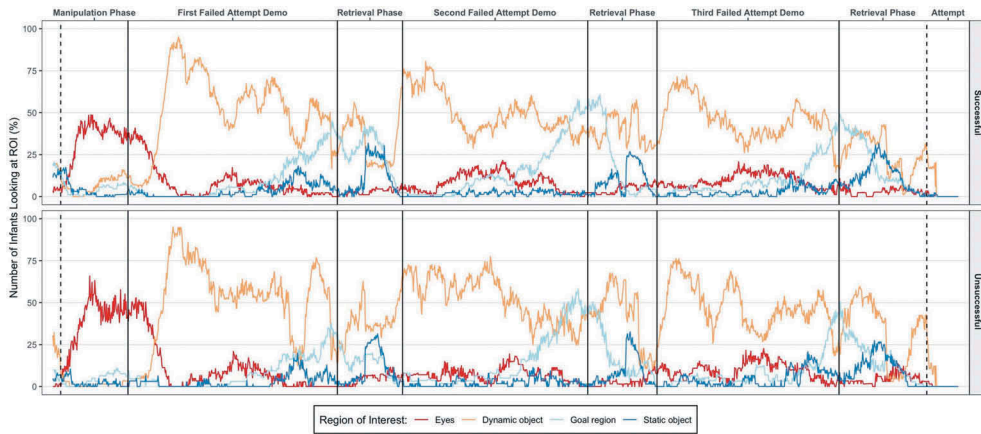


**Figure 4.** Average percentage of time spent looking at a Region of Interest relative to the total amount of looking time of infants across conditions.

*Eye-tracking measures: spatiotemporal regions of interest analysis*

Figure 5 depicts the percentage of infants looking at each ROI<sup>2</sup> per time frame during the failed attempt demonstrations for infants who correctly performed the target affordance (Figure 5 upper panel) and for those who did not (Figure 5 lower panel). Most infants tended to look at the eye-region during the manipulation phase (where the conditions differ), after which they followed the object movements as the model conveys one object to the other three times in succession. Remarkably, the eye-movement patterns are quite similar for both groups, irrespective of whether the infant is successful or unsuccessful in realizing the target affordance right after the demonstration. This reveals that although the conditions yielded significant differences in terms of affordance realization, the effects of these manipulations on infants' looking behavior when watching the failed attempt demonstrations must be quite subtle.

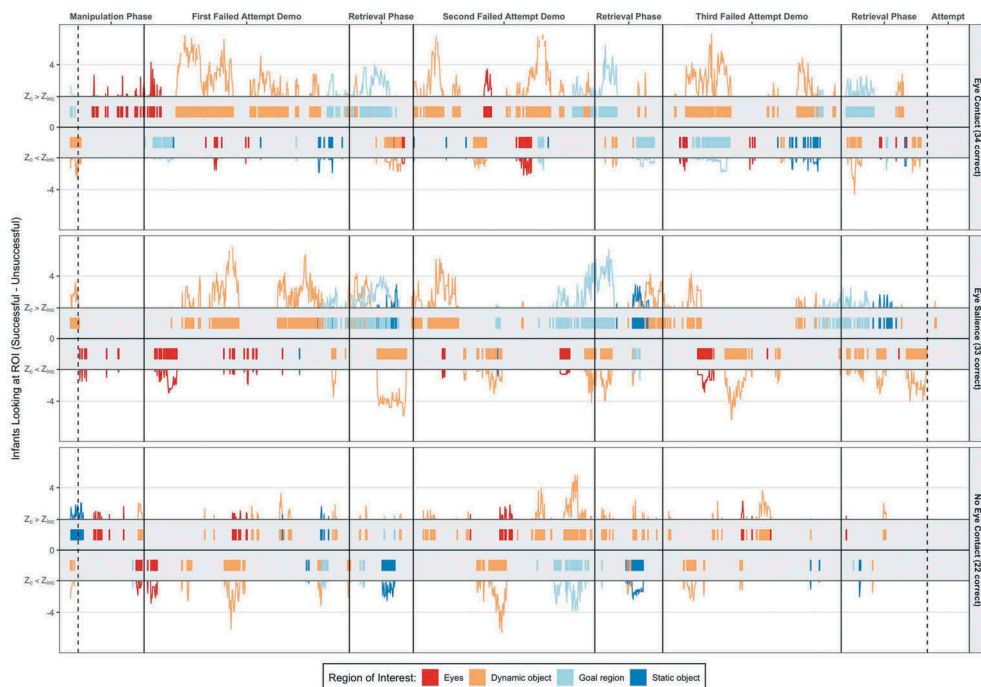
<sup>2</sup>Note that for clarity of presentation, the ROIs 'Static Object' and 'Other' were not included in Figure 5, Figure 6, or in the discussion of the results, because the groups did not display any relevant difference in timing or amount of looking for this ROI.



**Figure 5.** Time series displaying the percentage of infants looking at an ROI (different lines) at a given time, averaged across conditions. The upper panel shows infants *successful* in affordance completion, the lower panel the infants that were *unsuccessful*.

In [Figure 6](#), the time courses of successful and unsuccessful attempts as displayed in [Figure 5](#) were z-transformed and turned into a difference series in which positive z-scores indicate relatively more infants who produced a successful attempt were looking at the ROI and negative z-scores indicate relatively more infants who produced an unsuccessful attempt were looking at the ROI. The z-scores were calculated following the procedure one would follow conducting a z-test of observed versus expected proportions. There were five mutually exclusive ROIs, so we considered the expected proportion of infants looking at a specific ROI  $n$ , at a specific point in time  $t$ , denoted as  $ROI(n, t)$ , to be  $1/5$  ( $p_0$ ), a priori, and consequently, not looking at  $ROI(n, t)$  to be  $1 - p_0$ . The observed proportion ( $p_1$ ) was simply the number of infants observing  $ROI(n, t)$  divided by the total number of infants observing an ROI at  $t$  ( $N_t$ ). From this information a proportion Z-score can be calculated whose magnitude reflects the deviation of the observed proportion from the expected proportion as  $Z(n, t) = (p_1 - p_0) / \sqrt{p_0(1 - p_0) / N_t}$ . The time courses of successful and unsuccessful attempts were standardized separately in order to account for the differences in  $N_t$  between infants producing successful and unsuccessful attempts when rescaling the data. By design, the difference between these Z-scores (correct – incorrect,  $Z_c - Z_{inc}$ ) at time  $t$ , reflects whether an  $ROI(n, t)$  was observed more often than expected, by infants who made a correct attempt (positive Z values) or an incorrect attempt (negative Z values) at realizing the affordance.

In order to provide some notion of whether these differences were substantial, we focus only on values outside the range of  $-1.96 < Z < 1.96$ , or, a difference of about two standard deviations in both directions. In [Figure 6](#) all values falling within this range are masked by a grey panel on top of which line marks are drawn whose color corresponds to the ROIs of which  $Z_c > Z_{inc}$  (positive Z) or  $Z_c < Z_{inc}$  (negative Z). In effect, the two-colored bands in the center of each graph provide a description of the average time course of ROIs that most likely produced successful and unsuccessful re-enactments of the model's failed attempts in each condition.



**Figure 6.** Difference score times series of successful infants (top of each panel) versus unsuccessful infants (bottom of each panel) across all conditions. The y-axis represents the proportion Z scores. The EC condition is in the top panel, ES condition in the middle panel, and NEC in the bottom panel. The color codes in the center of the graphs indicate whether significantly more successful or unsuccessful looked at a specific ROI (see text for details).

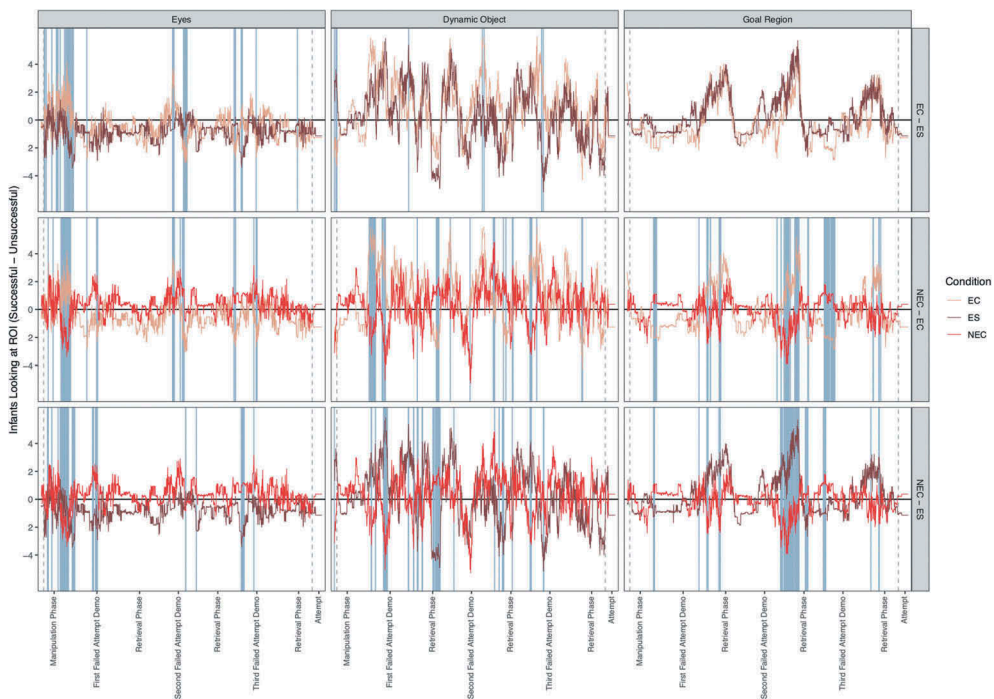
Figure 6 reveals various differences between the conditions and between the successful and unsuccessful groups.

One noticeable difference is that successful infants were looking more towards the dynamic object as it moved towards the goal region than unsuccessful infants during the failed attempt demonstrations. This difference was significant for 798 timestamps ( $\approx 13$  seconds) on average per failed attempt demonstration. In addition, successful infants tended to look more at the goal region when the model conveyed the dynamic object in close proximity to it. Remarkably, successful infants also tended to look more at the goal region significantly more during the retrieval phase. On the whole, successful infants looked at the goal region significantly more than unsuccessful infants for 270 timestamps ( $\approx 4.5$  seconds) on average per failed attempt demonstration during the retrieval phase. Instead, unsuccessful infants tended to look more at the dynamic object for 210 timestamps ( $\approx 3.5$  seconds) when the model retrieved the object towards the starting position of the failed attempt demonstration. The aforementioned differences, however, seem only to be the case across successful and unsuccessful infants within the EC and ES conditions. On the whole, differences in looking behavior (i.e. differences in proportions of looking at certain ROI at certain timeframes) between successful and unsuccessful infants are smaller for infants in the NEC condition, compared to the EC condition ( $P_{EC} = 0.58$ ,  $P_{NEC} = 0.24$ ;  $Z_{EC-NEC} = 20.96$ ,  $p < .001$ ) and ES condition ( $P_{ES} = 0.57$ ,  $P_{NEC} = 0.24$ ;  $Z_{ES-NEC} = 20.82$ ,  $p < .001$ ). In addition, the differences in looking behavior between successful



and unsuccessful infants across the EC and ES conditions were comparable ( $P_{EC} = 0.58$ ,  $P_{ES} = 0.57$ ;  $Z_{EC-ES} = 0.60$ ,  $p = .33$ ).

To assess the influence of condition type on the difference scores between correct and incorrect within each condition, a permutation test was used in which we focussed on difference scores in looking at the 1) eyes of the model, 2) the dynamic object and 3) the goal region where the dynamic object and static object can be combined. Figure 7 displays comparisons across conditions of the time series of difference scores between successful and unsuccessful infants per region of interest and per condition. Significant differences are marked by the light blue vertical bands. Looking at the eye region in the EC and ES conditions prior to the failed attempt demonstrations is related to successfully find the target affordance after whereas this is not the case for infants in the NEC condition (note that the whole face of the woman was not visible for infants in the NEC condition during this phase). For the ROI related to the dynamic object, there are hardly any significant differences between the EC and ES conditions. However, for the ROI related to the dynamic object, both the EC and ES conditions differ from the NEC condition significantly during the timeframes in which the model looks at the dynamic object for the first time. Specifically, more successful infants in the EC and ES conditions tend to look at the dynamic object right after the model shifts her gaze towards it whereas this difference



**Figure 7.** Presented are comparisons across conditions (EC and ES in the top panel, NEC and ES in the middle panel, and NEC and EC in the lower panel) of the time series of difference scores between successful and unsuccessful infants per region of interest (Eyes in the left panel, Dynamic Object in the middle panel and the Goal Region in the right panel). The y-axis represents proportions of Z scores. The vertical colored bands indicate significant differences across the conditions according to a permutation test.

between successful and unsuccessful infants is absent across infants within the NEC condition. The reverse pattern can be seen during the phase in which the model retrieves the object to the initial location in order to prepare for the second demonstration: Not only are successful infants likely to look at the goal region during this phase (as noted before), but successful infants in the EC and ES conditions are likely to do so more than successful infants in the NEC condition.

## Discussion

In the current study, we investigated whether attracting the attention of infants towards the eyes of a model before she performed a failed attempt to combine two objects would promote affordance realization by infants thereafter. Previous studies have shown that attracting the attention of infants towards the eyes of another promotes gaze following by following head turns (e.g. Senju & Csibra, 2008) and eye-turns (de Bordes et al., 2013). We reasoned that the gaze of the model can inform the observing infants about the opportunities for action the model is trying to realize by manipulating the objects, and this likely enables the infants to learn which actions the objects might afford (i.e. affordance learning), even though the model fails at her attempts. Following the gaze of another person could facilitate learning about a specific affordance by means of directing the attention of infants towards relevant actions on (parts of) objects. As the actions performed by the model all belong to the action-repertoire of the observing infants, we predicted that infants had a bigger chance to realize the target affordance after their attention was drawn towards the model's eye region (socially or artificially) prior to the failed attempt demonstration than if their attention was directed towards the head region in a non-specific way.

### *Eye-salience manipulations*

We found that when the model's eyes were made salient prior to each demonstration, either as part of an ostensive signal (eye contact) or artificially (blinking and moving dots covering the eyes), the success rates of infants in realizing the target actions afforded by the objects were higher (65%) than when the entire head region of the model was covered (46%). We did not find a difference in affordance realization between the eye contact and eye salience conditions, which replicates earlier findings indicating that drawing the attention of infants to the eye region prompts infants to follow gaze, irrespective of how their attention was drawn towards the eyes (i.e. ostensively or non-ostensively; see de Bordes et al., 2013; also see Gredebäck et al., 2018; Szufnarowska et al., 2014 for similar results). The suggestion that gaze following plays a facilitatory role might also explain why Belagamba and Tomasello (1999) found that most 18-month-old infants but not 12-month-old infants were able to carry out the correct actions after seeing a failed attempt demonstration. Proficiency in following eye-gaze seems to reach a functional level only from 18 months of age (Corkum & Moore, 1995), allowing the 18-month-olds but not the 12-month-olds to benefit from observing gaze behavior in their study.

These results do not imply that making the eyes salient in the EC and ES conditions is either a necessary or sufficient condition for infants to successfully realize the target affordance. The average success rate of the infants in the NEC condition was still 46%

(also see Shneidman et al., 2014 for comparable results with 18-month-olds). Also, in the study by Huang and Charman (2005; Experiment 3), 56% of the infants were still able to successfully re-enact the failed attempt when it was executed without a model being visible, indicating that the object movements themselves, naturally draw the attention of infants towards crucial parts of the object and actions onto the objects that can lead infants to realize the target affordance.

Huang and Charman (2005) used the concept of stimulus enhancement in order to explain why infants in their study were able to realize the target affordance after seeing the failed attempt demonstration or the 'ghost' failed attempt demonstration. Stimulus enhancement, such as object movements, directs the attention of the observer to an object, increasing the chance that observers manually explore that object and discover its affordances thereafter (see Fritz et al., 2000; Galef, 2013; Heyes et al., 2000; Hopper, 2010; Hoppitt & Laland, 2013). However, it might be that when object movements (and gaze alike) directs the attention of the observer towards specific actions performed onto that object, affordance learning can occur based mainly on these observations alone instead of manual exploration after viewing the demonstration. In this sense, object movements and the gaze of the model are not merely drawing the attention towards the objects that increases the chance that infants interact with the objects. Rather, the object movements and the gaze of the model might guide (or educate) the perceptual system of infants by which their perceptual system attunes to critical aspects of the failed attempt through which infants can learn a certain affordance while viewing the failed attempt demonstrations. In the current study, this point is illustrated by the fact that infants in the EC and ES conditions needed less exploration time compared to infants in the NEC condition in producing the target act.

### ***Spatiotemporal structure of eye-movements***

The analysis of the spatiotemporal structure of eye-movements of infants allowed for a closer look at how the model's gaze directed and guided the attention of infants, leading them to attune to critical aspects of the failed attempt demonstrations through which they could learn affordances. Although most infants followed the object movements performed by the model, infants that were successful at realizing the target affordances in the Eye-Contact and Eye-Salience conditions followed the object movements that *matched* the gaze direction of the model during the failed attempt demonstrations in comparison to unsuccessful infants in these conditions. Specifically, successful infants in the EC and ES conditions looked at the object movements more often while the model conveyed one object towards the other *before* she 'failed' to combine the two than unsuccessful infants in these conditions. In addition, the successful infants in the EC and ES conditions also looked significantly more at the goal region just before and after she 'failed' in comparison to unsuccessful infants in these conditions and successful infants in the NEC condition. In our view, the looking patterns of the successful infants in the EC and ES conditions closely resemble, and thus specify, the actions necessary to relate the dynamic object with the stationary object by which the infants were able to realize the target affordance shortly after viewing the demonstration. In contrast, unsuccessful infants across conditions looked at the object movement in a less-specific manner. For instance, they looked more often to the object movements *after* the model failed to realize the target affordance and retrieved

the objects towards the initial location, which is deemed as less informative for realizing the target affordance. So, although both groups looked at the same regions of interest for an equal amount of time, the difference in the temporal order in which infants looked at the object movements as a function of condition seems to be crucial for producing a success or not.

In order to directly assess the effect of condition, we compared the sizes of difference scores between infants that were successful and infants that were unsuccessful in affordance realization across conditions of looking at the eyes, dynamic object and goal region across the time series. When looking at the differences between successful and unsuccessful infants across conditions in general, it is noticeable that the looking pattern differs between these groups in the EC and ES conditions but not in the NEC condition. Specifically, we found significantly larger difference scores in the ES and EC conditions of looking at the eye-region of the model prior the failed attempt demonstration and looking at the dynamic object right after the model shifts her gaze towards it for the first time in comparison to the NEC condition. This means that in EC and ES conditions, success was more strongly related to looking at the eye-region of the model prior the failed attempt demonstration and looking at the dynamic object right after the model shifts her gaze towards it for the first time than the success of infants within the NEC condition. In the NEC condition, the eyes were made invisible at the start of the demonstration so initial gaze following and subsequent matching of gaze could not have led to subsequent differences in looking behavior between successful and unsuccessful infants. This result combined with the previously noted result that more infants in the EC and ES conditions were successful than infants in the NEC condition suggests that the manipulation, making the eyes of the model salient or not at the start of the failed attempt demonstrations, worked as intended: whenever the eye-region was made salient, infants had higher success rates in finding the target affordance and of this successful group, more of them looked at the eye region and matched the subsequent eye-gaze directions of the model in comparison to successful infants in the NEC condition.

### ***Limitations and future directions***

Huang and Charman (2005) have shown that infants produce the target acts, independent of whether they viewed the demonstrations live or not. Therefore, we chose to present the failed attempt demonstrations on a video screen with an inbuilt eye-tracking system instead of live-failed attempt demonstrations in order to avoid possible and unintended differences in the demonstrations across infants. In addition, this allowed us to measure the eye-movements of infants and analyze differences between them based on subtle variations (i.e. the conditions contrasts). However, this study setup refrained us to measure and analyze the dynamic interaction and coordination of gaze between the infant and the model that occurs naturally (see Yu & Smith, 2013, 2017 for examples). This could further elucidate how infants and their caregiver adapt and attune their behavior dynamically in ways that allow infants to learn effectively.

Next, we choose to analyze the behavior of infants on a group level, assuming that infants across conditions react in similar ways. However, there are probably multiple ways in which infants can learn affordances based on demonstrations as used in the current

study. Whereas some infants benefit a lot from using the gaze of a caretaker in learning affordances, others might depend more on the object manipulations that lead them to manually explore the objects from which affordances can be learned or perhaps a combination of two. This multicausality in learning and development is easily overlooked when looking for main effects of study manipulations but should be a topic of future investigation in order to better understand the complex interplay of contextual and personal factors that causes the observed variability of learning success across infants (see Thelen et al., 2001; Yu & Smith, 2017).

Finally, it should be noted that the retrieval phase is usually ignored in paradigms like the Re-enactment procedure (e.g. Bellagamba & Tomasello, 1999; Huang & Charman, 2005; Meltzoff, 1995;). However, the analysis in the current study reveals that it actually might be a highly relevant part of the demonstration phase as looking at the dynamic object being moved away from the other object might specify anything but combining the two objects together in a specific way, possibly refraining infants to learn the target affordance. Therefore, in future studies, attention should be devoted to what infants can observe before, between and after the experimental of learning phase.

The idea that social learning requires a form of social bias of the infant (e.g. intention detection) has thus far been tackled in studies showing that infants can realize object affordances with objects at a similar rate of success after seeing either a social or a non-social demonstration with those objects (e.g. Horne et al., 2009; Huang et al., 2002; Thompson & Russell, 2004; also see Heyes (2012) for a similar view on animal learning). As an alternative to these social biases and following theories of direct perception and ecological psychology (Gibson, 1986; Gibson & Pick, 2000; Meagher & Marsh, 2014; Thelen et al., 2001), we argue that social information like gaze direction is picked up and used similarly as other information in our physical environment, that is, as specifying affordances by attuning the perceptual system (Gibson, 1986; Gibson & Pick, 2000; Haith, 1998; Hellendoorn, 2014; Ingold, 2001).

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